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Advancements in power electronics and drives in interface with growing renewable energy resources

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ABSTRACT

The whole world is now concentrating on advancing their pool of renewable energy resources. Immense growth has happened in the field of renewable energy and the energy harvesting methods in the past decade. It is estimated that there is still a huge potential of growth remaining in the field of renewable energy resources in the coming years. Generation of renewable energy at the source end to the transmission of the energy to the utility end is done at various interstates coupled with power electronic equipments and systems. Applications of power electronics are expanding at a high pace in industrial power generation, utility, grid integration, and transmission environments due to the advancements in technology and reduction in cost and size of the components and systems. There are numerous multistage converters and inverters topologies being developed for processing and delivering the gigawatt level of renewable power being produced. This paper highlights the growth of power electronics starting from semiconductor type switching devices to various multistage topologies which will extensively contribute to the development and growth of renewable energy resources around the globe. It is a fact that power electronics is an integral part of renewable energy generation and utilization and its optimization of size, cost, and performance is necessary for the most efficient harvesting. Latest advancements in the various ratings of switching devices and components are discussed in the paper. Proper topology based implementation of power electronics and motor drives in the generation of various renewable energy sources such as solar power, wind power, fuel cells, biomass, and other energy storage elements are discussed in details. Individual sources of renewable energy resources interfaced with multistages of power electronic systems are elaborated in the paper.

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1. Introduction

Due to the shortcomings and the threats posed by the conventional fossil fuel and the nuclear power sources, the whole focus is now shifting towards non-conventional or alternative sources of fuel. RERs and non-polluting sources of energies such as solar, wind, fuel cell, and biomass energies have enormous potential to supplement the conventional sources of electric power generation. The increasing number of RERs and distributed generators (DG) would require new strategies and methods to maintain the operation and regulation of electric power into the hybrid grid. The quality and reliability of electric power at the utility side depend on the efficiency and sustainability of the increasing number of advanced PE interfaces. Advanced motor drives are greatly influencing the energy generations from wind power, hydropower, biogas, and energy storage systems such as flywheel energy storage.

PE is an integral part which connects the RERs to the utility grid. PE in the past few decades has undergone remarkable technological advancement and evolution due to the development of fast and high power semiconductors and the real-time controllers capable of handling complex control algorithms working in a robust environment. The world wide growth of PE technologies in the next few years is going to be gigantic. PE finds very wide range of applications in all kinds of RERs. Growth of semiconductor electronics and the impact on the high power multi-stage PE converter and inverter topologies are elaborated here. Due to the advancements in semiconductor technologies, high power IGBTs and IGCTs are available for mid and higher range of PE converters and adjustable speed drives. Various ranges of switching devices for high power switching applications are elaborated here based on their high current and power ratings.

Several PE rectifier topologies are demonstrated, which will find wide scopes in rectification of high level of AC to DC power. Multi-stage converters as well as matrix and hybrid matrix converters are identified which are extensively being used in MW range of power in RERs. Finally, multi-stage inverter topologies are addressed which finds extensive application in RERs for power conversion especially from the DC bus to AC utility grid.

In the last section of the paper all individual RER generation units such as solar, wind, fuel cell, biomass, supplying the utility grid are elaborated. Different stages of the power conversion of the RERs are shown and discussed in details. In addition, energy storage elements such as battery energy storage systems (BESS) and flywheel energy storage systems (FESS) which are connected to the utility grid in conjunction with other RERs are exemplified. All kinds of possible applications of PE rectifier, converter and inverter topologies and circuitries in application to the energy conversion process of the RERs are discussed here.

2. Growth trends of renewable energy resources (RER)

Renewable energy sources such as solar power, wind power, geothermal, biomass, and hydropower are becoming an increasingly important part of every nation's electricity fuel mix. Renewable sources produce minimal environmental impact and generally have little or no fuel costs.

There is a remarkable development of RERs, being projected across the globe as shown in Fig. 1 The rate of growth of RER from 2004 to 2008 has not been that significant. But starting 2009 there has been a global move towards more of green energy or clean coal technology which has resulted in considerable amount of growth in the past year as projected in Fig. 1.

The growth in RER is no longer confined to the developed world. There are significant prospects of RER expansion happening in developing countries. Despite the continuing upward trend of renewable energy growth and the positive achievements, the world has extracted only a small portion of the RER. RER development policies and efforts are now continuously being investigated in order to strengthen the development to the next level. This continuous process of enhancements of energy policies leading to a great market penetration of RER in the energy sector will play a critical role in building a long-term, stable, low-carbon global green economy. There are significant investments happening in different areas of RERs around the globe as shown in Fig. 2. Based on the recent trend of fastest growth ever in the field of RER, it can be projected that the world wide investments in the field of renewable energy is going up by manifolds as projected in Fig. 3 [1–5].

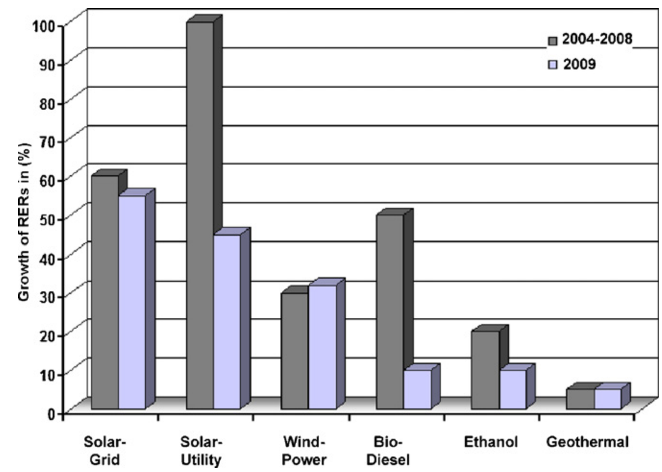

Fig. 1. Approximate global annual growth in (%) of renewable energy resources [1].

3. Advancements of power electronics and drives

In the past few decades, power electronics has emerged as a major discipline in science and technology, which has application in almost any areas. In this gradual process power electronics has become an indispensable tool for modern industrial automation and control, energy efficiency systems, and all kinds of power and energy conversion and conservation systems. Power electronics has an influential role in the industrial and energy policies of various nations. It plays a dominant role in renewable energy systems and in solving the global warming problem, which is one of the most important issues across the world.

Power electronics and the related technologies have seen dynamic evolution in the recent past. Power electronics has wide

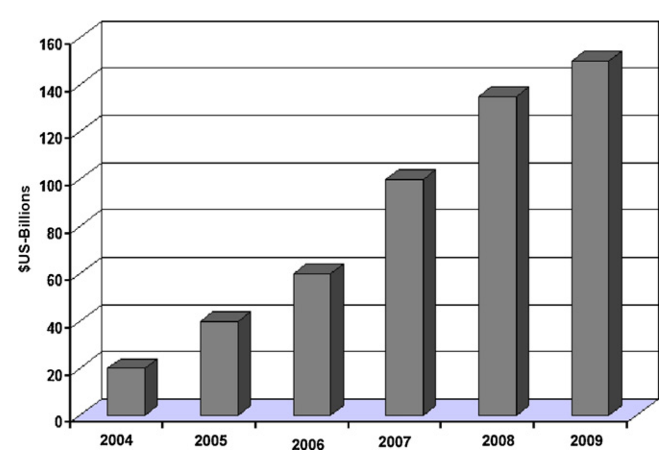

Fig. 2. World-wide annual growth in investments in renewable energy resources [1].

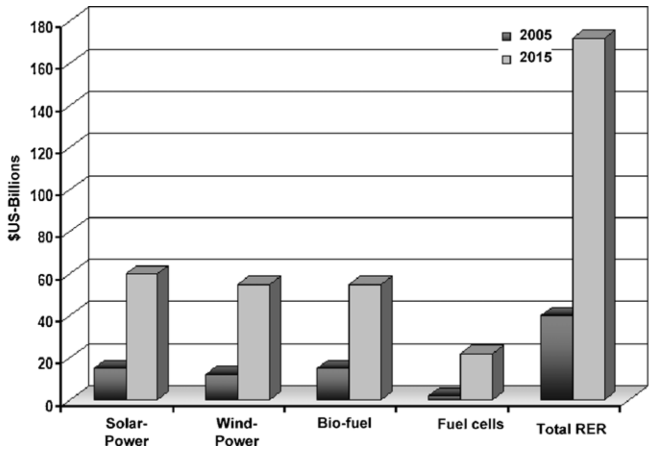

Fig. 3. Projected global annual growth of renewable energy resources market in US ($).

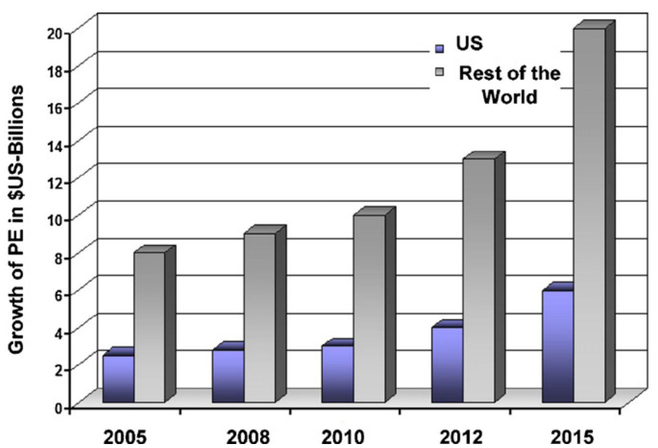

Fig. 4. Estimated growth of PE market over the years.

variety of applications such as in renewable energy based power systems, aerospace, and military environments primarily due to the advantages of cost, size reduction, and performance improvement. The primary focus of this century is in the global industrial automation and sophisticated control, energy conservation, and environmental pollution control trends where the scope of power electronics is inevitable. Role of power electronics in our society in the future will be more extensive and comprehensive. The main focus of this paper are the recent technological advances of power semiconductor devices, converters, various motor drives, and advanced control and estimation techniques applicable to renewable energy systems. Projected global growths of PE market over the years are shown in Fig. 4.

The recent advancements in power electronic technology have helped it play a very important role in interfacing various RERs and their integration into the grid. Roadmaps are being devised for developing the power electronic interface for the highest projected turbine rating, to optimize the energy conversion and transmission. New topologies and filter networks are being designed to minimize harmonic distortion, to optimize the cost and efficiency over a wide power range, and to have a high reliability and tolerance to the failure of a subsystem component [5–16]. Various applications of PE in interface with emerging RERs are shown in Fig. 5.

3.1. Growth in semiconductor electronics

In the recent past, power electronics has undergone a very fast evolution, which is mainly contributed by the advancement of fast semiconductor switches which has high power handling capability. There are other factors such as complex power electronics based sophisticated real-time controllers which can implement complex control techniques at a reduced price for the renewable energy systems. Continuous increase in semiconductor device efficiency and reliability at lower costs drives power electronics into distribution applications.

The main factors which contribute to the device selection criteria are the cost, efficiency, reliability, and physical dimension. Thus, the selection criterion will summarize to lower cost, higher reliability and ruggedness, level of high voltage and current ratings, and higher frequency operation.

Some of the notable exceptions are high voltage DC (HVDC) to transmit DC power over large distances at up to 1 MV and static VAR compensators (SVC) to control inductors or capacitors for voltage stabilization. All these have relied on phase control thyristors (PCTs) to control power primarily because these devices offer the highest power control and hence the most cost-effective solutions. The power generation industry has little call for power electronics at the output stage since the powers are typically very large (250 MW) and generators operate in synchronism with the infinite grid [6–9].

There are multidimensional and multi-structural applications of power electronics. The solid-state power electronic apparatus are considered as a high-efficiency switching mode power amplifiers, with extreme high level of efficiency. With the increase in the cost of energy, future energy conservation with the help of power electronics will be considered extremely important. Significant changes in power electronics are brought by the advancements of Si-based power electronic devices in terms of power rating and characteristics. The emergence of numerous semiconductor devices is shown in Fig. 6. Various ranges of high power semiconductor devices suitable for RER applications are shown in Table 1.

A comparative chart for various switching devices in application to the RER is shown in Table 2. Development of power electronics and power devices is directly related to the renewable energy systems. Some of the major areas are fuel cells, PV cells, microchips, ultra capacitors, superconducting magnet energy storage systems which significantly impact power electronics evolution. Power semiconductor devices are the core of power electronics, the research of power semiconductor devices strictly falls into the mainstream of power electronics technology.

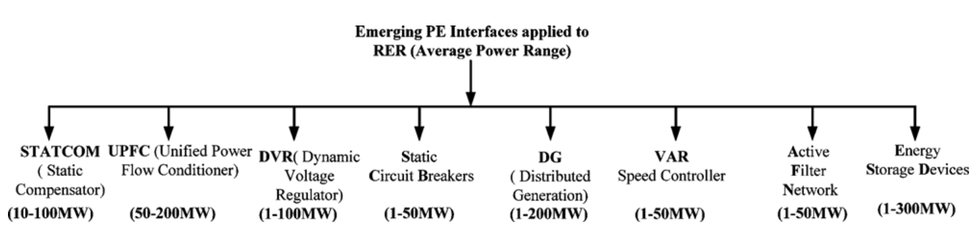

Fig. 5. Different applications of PE with respect to RER.

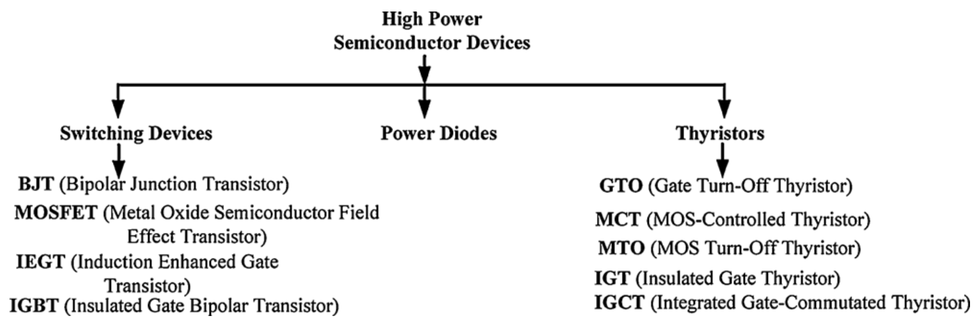

Fig. 6. Development of high power semiconductor devices.

Table 1
Semiconductor devices for high-power applications.

Device-types	Ratings (kV)
MOSFET (Si)	0.1–0.5
IGBT (Si)	0.5–6.5
GTO (Si)	4.0–9.0
Thyristor (Si)	5.0–11.0
MOSFET (SiC)	1.0–2.0
BJT (SiC)	1.0–5.0
IGBT (SiC)	3.0–10.0
GTO (SiC)	10.0–25.0
Thyristor (SiC)	10.0–40.0

Table 2
Comparative chart for switching devices for high-power applications.

Device	Switching speed	Gain	Efficiency	Control parameter	Current rating
IGBT	Fast	High	Low	Voltage	2 kA
IGCT	Very fast	Medium	High	Current	4 kA
GTO	Medium	Medium	High	Current	10 kA

3.2. Advancements in high and medium power drives

Electrical machines which are the workhorse of advanced variable-frequency AC drive have gone through sustained progression during the past few decades. With the introduction of modern powerful digital computers and processors, new and improved material science has resulted in motor drives with higher density, efficiency, and performance. Latest advancements in high power semiconductor devices, high power inverter and converter topologies, advanced PWM control techniques, and innovative control and regulation methods have contributed significantly to the motor drives industry specially for high and medium power applications such as in RERs. Various types of machines and the motor drives are shown in Fig. 7. Induction and synchronous machines are extravagantly used in RERs. Particularly the wound-rotor induction motor drives have been used in defined speed range for large size pumps, compressors, variable-speed hydro, advanced flywheel energy storage, and modern wind power generation systems. On the other hand, the cage-type induction motors with voltage-fed or current-fed converters in wide power range are universally popular in industrial applications. Especially field-wound synchronous motor drives are quite popular due to the simple thyristor-based converter topology and improved efficiency. Voltage-fed and current-fed multilevel converters are being universally used now for high-power all quadrant induction as well as synchronous motor drives. The SRMs are considered for many applications in comparison to induction machines because of their simple construction, robustness and relatively lower price.

4. PE in interface with renewable energy resources (RER)

Power electronics has wide variety of applications starting from residential, commercial, industrial, transportation, utility systems, telecommunications and aerospace systems. The main branch of power electronics can be subdivided into controlled and uncontrolled rectifiers, converters, switch-mode inverters, and cycloconverters. Various types of rectifier topologies for high power drives applications are shown in Table 3. In general power electronics deals with conversion and control of electrical power in the wide range of few microwatts to several gigawatts by the use of switching mode power semiconductor devices. Different types of multi-stage converter topologies are shown in Table 4. Various multistage inverter topologies are listed in Table 5. Multiple modulation schemes for the high power PE converters and inverters are shown in Fig. 8. Power electronics has wide range of applications starting from switch mode power supplies, uninterruptible power supply

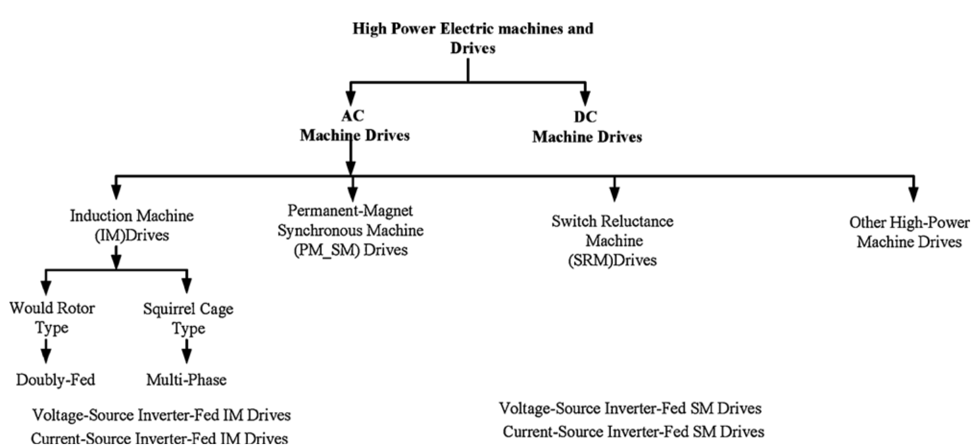

Fig. 7. Various types of motor drives applicable in RER generation.

Table 3
Various rectifier topologies for high-power applications.

PWM current source rectifiers	Multi-phase diode rectifiers	Multi-phase SCR rectifiers
Single-bridge	12-Pulse-series-connected-diodes	6-Pulse SCR
Dual-bridge	18-Pulse-series-connected-diodes	12-Pulse SCR
	24-Pulse-series-connected-diodes	18-Pulse SCR
	48-Pulse-series-connected-diodes	24-Pulse SCR
	Higher-pulse-series-connected	Higher-pulse SCR

Table 4
Numerous multistage converter topologies.

Multi-level converter topologies	Matrix converter topologies	Hybrid matrix-multiconverters
Diode clamps	Two-stage	Cascaded multi-level hybrid matrix converter
Bidirectional switch interconnection	Standard	
Flying capacitors		Flying-cap multi-level matrix converter
Multiple three/multi-converters		
Cascaded single-phase H-bridge converters		Multi-level H-bridge converter

Table 5
Various multistage inverter topologies.

PWM DC/AC inverters	Soft-switching DC/AC inverters
Single phase full bridge VSI, CSI	Diode clamped multistage inverter
Three phase full bridge VSI, CSI	Capacitor clamped multistage inverters
Other hybrid PWM VSI, CSI	Cascaded H-bridge multistage inverters
	Cascaded multistage VSI
	Other hybrid multilevel VSI

(UPS) systems, electrochemical and electromechanical systems and processes, heating and lighting control, electronic welding, power line compensator. In addition power electronic circuits are used in active harmonic filters, high voltage DC (HVDC) systems, photovoltaic (PV), fuel cell (FC), wind power, hydropower, and other renewable energy generation and storage systems. An example of a hybrid renewable resource based power system and their control network is shown in Fig. 9.

In addition, AC and DC link interfaces are very important connections between various RERs and grid network. Small modular RERs are interconnected through microgrids to the distribution systems via HFAC links. HFAC and HVDC links are connected for voltage stabilization and power regulation in a distributed generation system such as interconnected RERs. Various ranges of high power AC and DC link voltages are shown in Table 6.

With the penetration of distributed generation systems in a microgrid network, electricity market is immensely benefited. Due to the increase in the concentration of distributed renewable energy sources (DRES) and corresponding power electronic (PE) interfaces, the integration of these resources into a single network has become very challenging. In Fig. 10, various interfaces of power electronic networks in DC or AC type renewable energy generation systems are shown [4–8].

The main focus of this paper is the role of power electronic technology on the growth trends for renewable energy systems. Among all the current renewable energy sources, wind energy is the most advanced technology due to its modernization contributed by the recent improvements of the power electronics and control. In addition, economical reliability is another attractive point, which has resulted in the increase in the number of wind farms. On the other hand, PV or solar power based renewable energy systems has the drawback of being more expensive and less efficient. However, it is being forecasted as an important alternative in the near future with further technical improvements and cost minimization. On the other hand, technical research and development work are being extensively carried out on various energy-storage systems such as flywheels, hydrogen, compressed air, super capacitors, supercomputing magnetic energy storage (SMES), and pumped hydroelectric.

At present the growing trend is for the utilization of vast wind and PV resources, which are renewable, and environment friendly. However, use of both of these resources is heavily dependent on power electronics. With the recent advancements in technology in variable speed wind turbines, power electronics, and machine drives have made wind energy very achievable. However, solar power is currently more expensive than the wind power although the cost has gone down substantially in recent years.

Wind and solar resources are the bulk of electrical storage sources which is also profoundly controlled by power electronics where further cost reduction is essential. Thus, heavy emphasis on R&D of PV cells is being carried out for further substantial cost reduction in future. Due to the sporadic nature of these resources, they require back-up power from the grid. AC to DC rectifier circuits are typically used in order to generate a controlled or uncontrolled DC voltage from either a controlled or an uncontrolled AC source. Micro turbines, permanent magnet type wind turbines or the utility supply are few examples of AC sources which typically are uncontrolled. In the process of conversion from a utility supply, the rectifiers are used for DC linking of systems or providing DC voltage for specific load applications such as battery regulators and variable

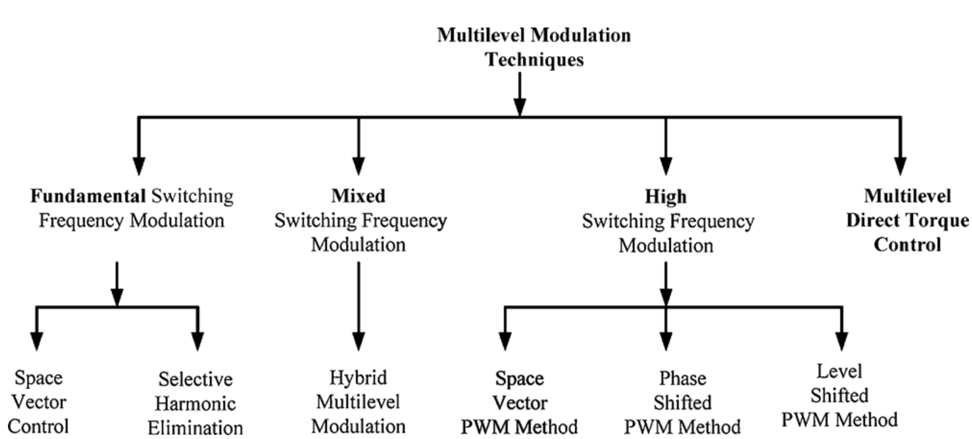

Fig. 8. Numerous types of modulation techniques implemented for multistage converters and inverters.

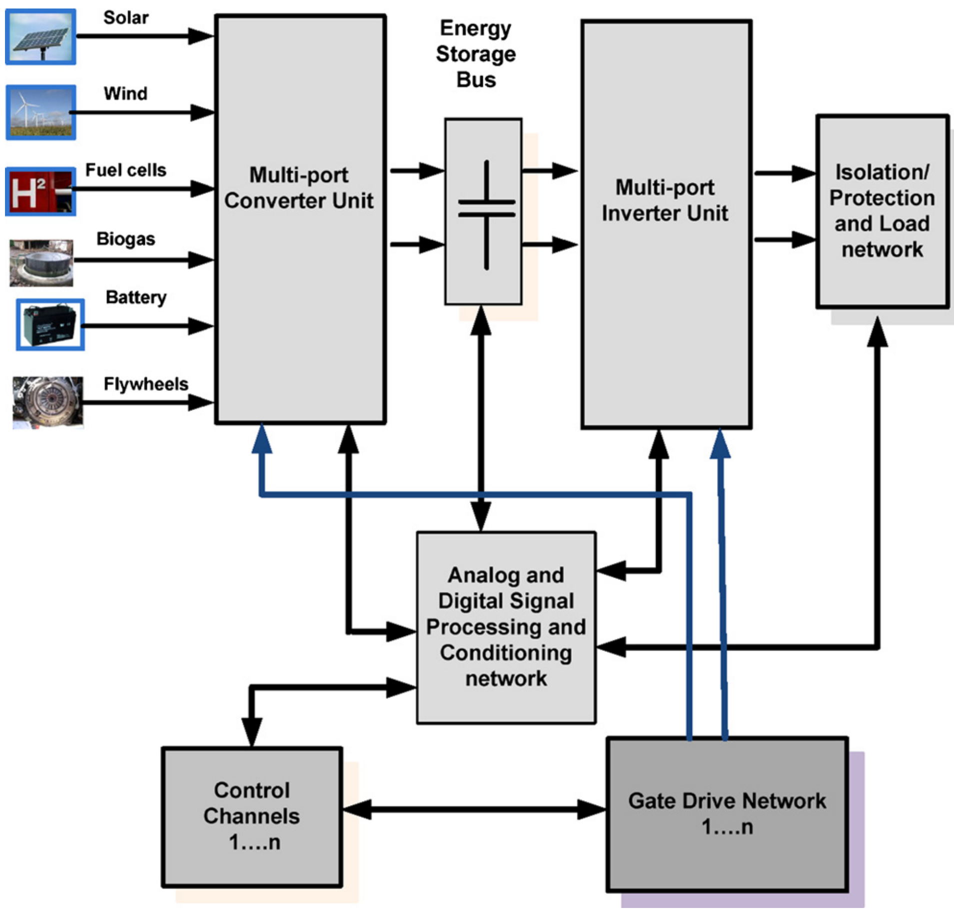

Fig. 9. Hybrid renewable energy sources interconnected and their control algorithm.

Table 6
AC and DC link voltage ranges for high-power applications.

AC-link (kV)	DC-link (kV)	Load-range (MW)
115–345	±250	100–500
230–500	±400–500	500–1000
345–500	±400–500	1000–2000
500	±500–600	2000–3000

Table 7
Parameters useful for PE interfaces RERs.

RE resources	Control parameters	Control objective
Solar power	V_{PV},I_{PV},P,Q,v_g,i_g	Maximum peak power tracking, power flow to the utility
Wind power	ω_g,P_g,V_d,I_d,v_L,i_L	Generator speed, current, DC bus voltage, grid/load current
Fuel cell	V_{DC},P_L,Q_L,v_L,i_L	DC bus voltage, power to the grid/load
Bio energy	ω_g,P_g,V_d,I_d,v_L,i_L	Generator speed, current, DC bus voltage, grid/load current
Energy storage (battery, flywheel)	V_{DC},P_L,Q_L,v_L,i_L	DC bus voltage, power to the grid/load

frequency drives. DC to DC converter circuits are very common type of PE interface in renewable energy system. In such cases, an uncontrolled and unregulated input DC voltage is filtered and regulated depending on the specific load applications. They are commonly found in PV battery charging systems. PV type energy sources are fed to converter circuits which are usually optimized for extracting the maximum power output of the PV array [6–38]. Different

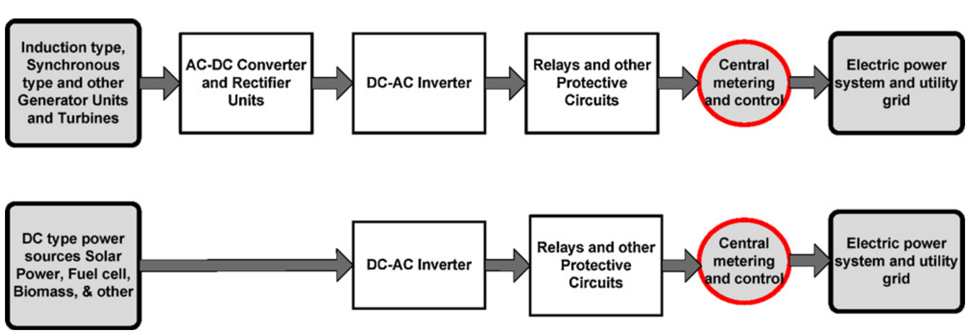

Fig. 10. Power electronic interfaces in the renewable energy network.

types of PE regulation parameters in application to RE generation and transmission process are listed in Table 7.

5. Various RER in interface with PE

5.1. Wind power and PE network

The biggest challenge in the wind power plant is to capture and transfer the optimum power to the grid. The main control objective is the wind speed, which is difficult to be tracked. It is difficult to control the synchronous or induction generator systems as well the rectifier system. Thus, the control of the dynamic system needs to be incorporated by the power electronic converters and inverters. A generic presentation of a wind generator conversion system interfaced with PE networks is shown in Fig. 11.

Generally in a wind farm, there are numerous wind turbines connected in different parallel combinations. Such turbines supply power to a common DC bus via power electronic systems. Now for the connection of this DC power to the grid, current controlled voltage source inverters can be used to deliver the power into the grid. The power electronics based voltage source inverters would generate an AC current that will follow a desired reference waveform. Thus by the use of control interface transfer of the captured real power and reactive power with minimal harmonic pollution is plausible.

Power electronic DC/DC converters are used to regulate the DC voltage of the power generator or rectifier units by varying the pwm duty ratio, so that the optimum DC voltage profile is maintained at the rectifier terminal for maximum power capture operation. An appropriate DC voltage is established at the DC bus to enable the voltage source inverters to perform the optimal real power transfer and reactive power regulation operations.

In the recent years there has been enormous advancement in variable speed wind turbines. To achieve variable speed operation, it is necessary to decouple the electrical grid frequency and mechanical rotor frequency. Thus, power-electronic converters in conjunction with advanced control systems play an extremely important role. The main disadvantage of a variable speed wind turbine is the need for a power converter which adds to the complexity and the cost of the system. There are certain advantages of variable-speed turbines among them the most important is that their annual energy capture is about greater than the constant-speed technology, and that the active and reactive powers generated can be easily controlled with the help of modern power electronic technology. Thus the flicker problem is not much intense in a variable speed wind turbine system.

Motor drives and PE are two integral part of the wind energy based power system. One of the special types if induction generator is doubly fed induction generator (DFIG), which utilizes the concept of variable-speed. When the turbine used for power generation is a variable speed turbine with DFIG, the power electronic converter would directly feed the rotor winding, and the stator winding is connected to the grid. With the help of power electronics it is possible to decouple the mechanical and electrical frequencies and finally variable-speed operation is achieved [39–45]. An example of an induction machine regulated wind power generation and control unit with PE interface is shown in the Fig. 12.

5.2. PV or solar power and PE network

Generally PV cells can be connected to the grid or they are used as isolated power sources. The major role of PE in PV system is to convert energy from one stage to another stage in the grid with optimum possible energy efficiency, and performance. The PE interface might be sources to multiple generator and loads. The example of a single stage grid connected PV network would be a PV source array, a inverter network, a controller stage followed by the utility grid. There are multiple inverter and PV array schemes based on the suitability of utility and performance requirements. Some are central structured inverters and some are string of inverters connected in a series and parallel mesh structure. Almost all the PV networks with either LF or HF transformer isolation schemes. The design of such isolation transformers must be optimized to minimize the losses and increase efficiency. Improvements in PE technology have lead DC/AC PWM inverter using IGBTs for switching upto 15–25 kHz for better performances. High frequency half and full bridge isolated converter topologies, single and double inductor based topologies are also being used nowadays. A PV network is shown in Fig. 13 connected to the grid via PE links.

There are many types of PV topologies based on the requirements in different geographical locations. Some countries do not require grid-isolation and thus more simple type of PE topologies can be implemented there. They generally use a boost stage connected to the PV arrays followed by the inverter network and the filter circuits finally feeding the utility grid. There are certain situations where DC/DC converter stage is completely ruled out. The PV arrays are directly hooked to DC/AC inverter stage followed my transformer isolation. On few other occasions PV sources are followed by only the inverter stage without using any kind of isolation in between and are directly coupled to the grid. Certain specific applications demand cascaded inverter stages where multiple inverter network structure is derived at the PV output to feed the grid or multiple grids [46–50].

There are numerous classifications of converter topologies which are made with respect to the number of power processing stages, use of network transformers and types of grid interface. In general there are two major types of control schemes used for controlling and regulating different converter topologies in any PV network. The two methods are duty cycle control and current control methods. In case of a module oriented converter comprising several modules common mode of connection is series mode on the DC side and in parallel mode on the AC side. The standard power ratings of such PV power plants are up to several megawatts. In addition, in the case of module integrated converter network topology, a converter per unit PV module and a parallel connection on the AC side are used. Thus, in such topology, a central measure for main supervision is necessary.

In convention, the classification of PV topologies is divided into two main categories namely PV systems connected to inverters with DC/DC converter (with or without isolation) and PV systems connected to inverters without DC/DC converter (with or without isolation). In both the PV networks connected with PE interface, an isolation using a transformer is used which can be placed on either the grid or low-frequency side or on the HF side. The physical dimensions of the line-frequency transformer make it an important component in the system. The HF transformer is very compact, but the correct use of the power electronic circuits will help to reduce the losses. Due to the isolation requirements in the US, the transformer is used in the circuitry. There are certain other topologies of PV network such as cascaded networks are used in many applications with the proper implementation of PE network. It is important for the PE inverter to perform multiple functionalities such as maximum power point tracking (MPP) control, grid-current control and voltage regulation and modification.

The main requirement for capturing the maximum power is a maximum power point tracker (MPPT). In a solar panel, the maximum power point is directly a function of solar irradiance and temperature. Several MPPT methods have been defined so far which can be implemented either in DC/DC conversion stage or in DC/AC inverter stage. These different methods vary in complexity of the circuitry, convergence speed, range of operation, and

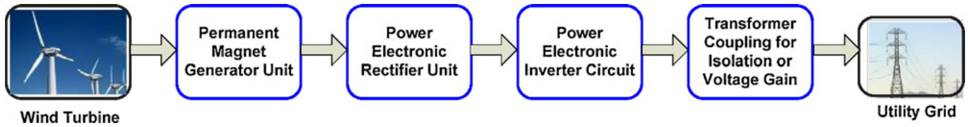

Fig. 11. Wind energy conversion system with power electronic interface.

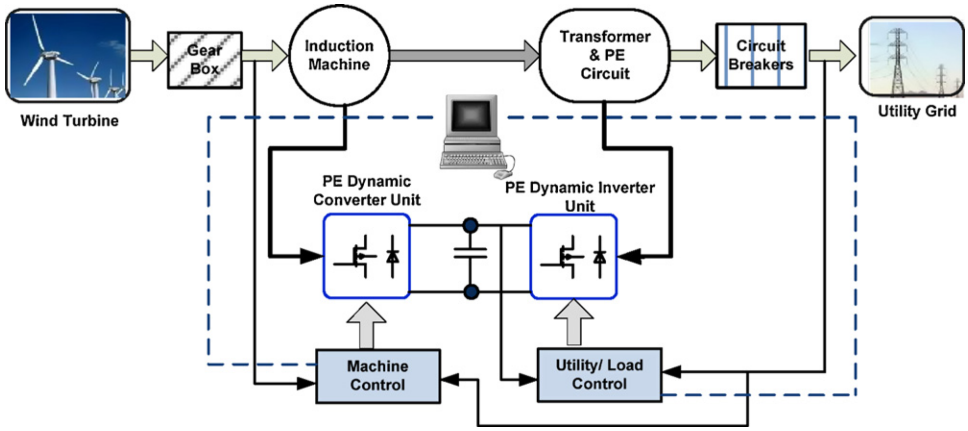

Fig. 12. An induction machine regulated wind power generation and control unit with PE interfaces.

cost. In some cases, a double-stage inverter is used for the MPPT. In such a situation, the very first stage DC/DC converter performs the MPPT and in the second stage the DC/AC inverter is dedicated to control of the grid current by means of pulse width modulation (PWM) scheme, space vector modulation (SVM) scheme, or other methods of control. There different types of MPPT methods used in DRES. Among the 'Perturb and Observe', 'Incremental Conductance', 'Constant Voltage', 'Fuzzy Logic' and Neural Network' are the most famous methods. It is the control schemes applied to PE converter and inverter stages which make MPPT successful [47].

5.3. Fuel cells, hydrogen generation and PE network

The increased need for renewable energy utilization and global pollution awareness has made green or renewable energy more and more important for stand alone as well as distributed generation. Among all the resources of renewable energy systems, two major technologies such as wind and photovoltaic technologies have a serious drawback that, these sources of energy can deliver power only when wind blows or the sun shines and thus cannot be used as a standalone independent generation resource. On the other hand, fuel cells systems have emerged as an important renewable energy resource. Fuel cell systems can be used as low and medium power residential applications, an uninterruptible power supply especially for houses, industries and remote locations as well as for automotive applications. Fuel cell (FC) generates DC power, which must be inverted to AC power and stepped up to for delivering the power to the utilities such as household applications as well as for distributed generation.

A typical characteristic of a fuel cell is that its voltage decreases almost linearly with the increase in load current; thus output voltage must be regulated at a defined load voltage. A suitable power electronic interface is necessary to be connected between fuel cell and utility grid, with the capabilities of voltage regulation, output voltage adjustment and isolation between FC and the load. Either a DC/DC converter is connected with the fuel cell tank in concatenation with a DC/AC inverter or a DC/AC inverter is directly coupled to a transformer is used to achieve the above conversion task. There are multiple topologies of switched mode DC/DC converter followed by DC/AC inverter is proposed so far. A conventional FC network has a switched mode DC/DC converter to limit the size and cost of the system followed by an inverter. Generally due to the reduced requirement of input filtering current fed DC/DC converter is preferred over a voltage fed DC/DC converter. Fig. 14 shows a schematic of FC based power systems driven by PE networks.

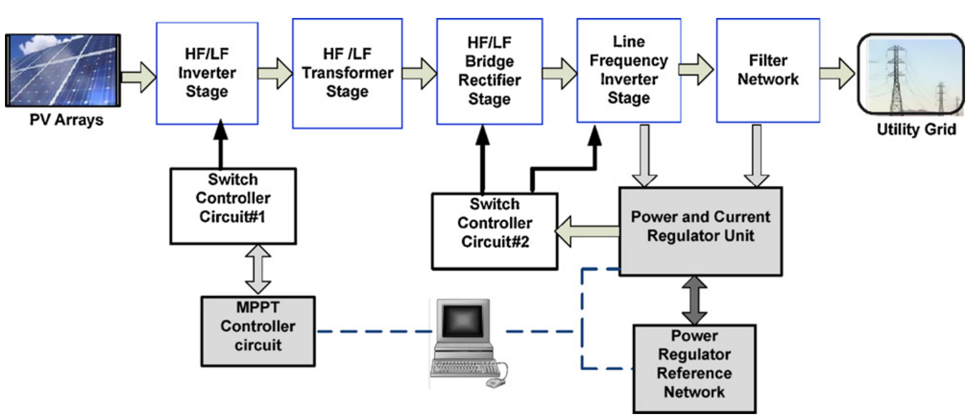

Fig. 13. PV network connected to the grid via PE links.

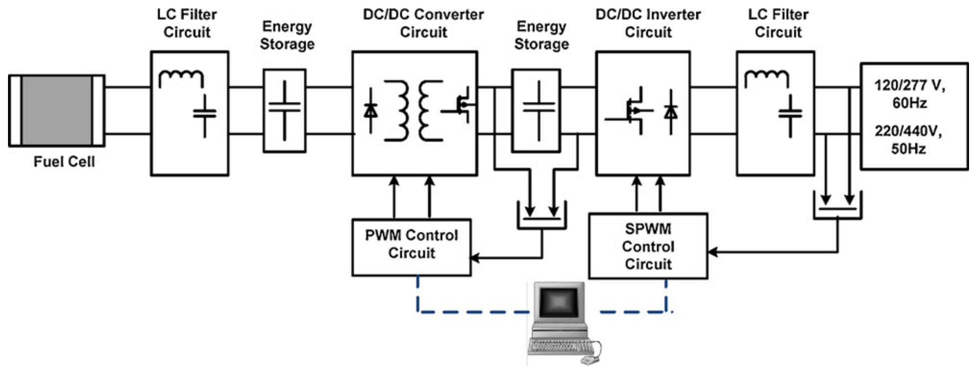

Fig. 14. Control network of a fuel cell based power system interfaced with PE devices.

Low and medium power applications require push–pull DC/DC converter as the choice which along with a voltage gain has the advantage of reduced switch conduction losses. High power applications demand the use of full bridge topology, since push–pull topologies have serious problems associated with center tap connection, which tends to cause saturation of the transformer at high power levels. Although a full-bridge topology consists of more switches of half rating, it is more economical and efficient. All of the above discussed power electronic topologies use multiple stage conversions to deal with the above mentioned challenges related to FC systems. These result in large component count, and finally poor reliability, high cost, and low efficiency.

Energy storage is another big area where the role of power electronics find much importance when connected to a FC system. Energy storage devices such as battery and ultra capacitors are also needed at various stages either to supply auxiliaries or to improve the slow transient response of the fuel cell in conjunction with a power electronic interface.

When fuel cell network is directly connected to a DC–AC inverter, along with a coupling transformer for adding loop gain, it becomes a single conversion stage. The coupled transformer which is used for step up operation as well as voltage gain provides the isolation between the fuel cell and the load as well. The major advantages of this topology are minimum component count and lower range of losses. The PWM operation of the inverter stage at high current becomes challenging, however development and easy availability of high current low voltage power semiconductor components offers motivation for the proposed scheme. However, the complexity gets transferred to formulating the design scheme; mathematical modeling and implementation of control techniques which needs to be addressed [51–54].

In general most common energy storage devices are batteries, capacitors and ultra-capacitors. When series of battery packs are placed across the FC stack, they require an additional circuitry for regulating the DC bus voltage. The cost of these multiple cells in series is very high and they have a short lifetime. This hybrid system needs a costly battery management system for safe operation.

5.4. Bio-gas/fuel technology (BGT–BFT) and PE network

A major source of biofuel is biogas. It typically produces methane and carbon dioxide unaided by oxygen drawn from decomposed organic matter. Continuously decomposing microbes and algae are the most common sources of biogas. Cost is one major advantage of biofuel as a renewable form of energy is that can help cope with the constant rise in fuel prices. Considering the prospect for a broader source of energy such as biofuel will lessen global dependence on imported fossil fuels. Due to the universal diversification of agricultural products in developing and developed countries as resources for the production of biofuel, it would emerge as an attractive opportunity to provide employment to the farmers and development to rural communities all across the globe. Biomass refers to the energy derived from the plant and other organic substances. There are a variety of biogas sources including the energy stored in trees, green crops, vegetable coal, and wastes from forests, urban and agricultural wastes which are prominent. There are several efficient methods of biomass energy utilization proposed recently. In order to generate combustible gasses, the biomass can be cooked or gasified. These gasses can be converted to liquid fuels known as biofuels namely ethanol and methanol. Sewage if properly treated would generate power by capturing the methane and utilizing it properly.

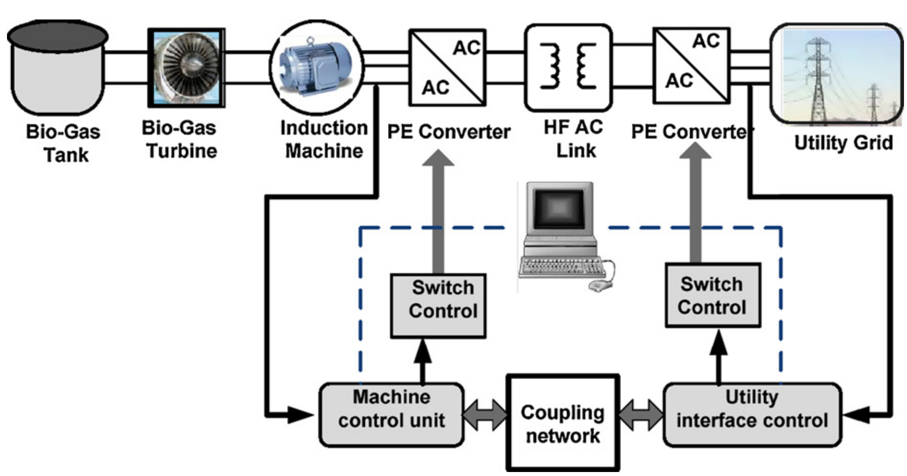

Fig. 15. Biogas based power system interfaced with PE network.

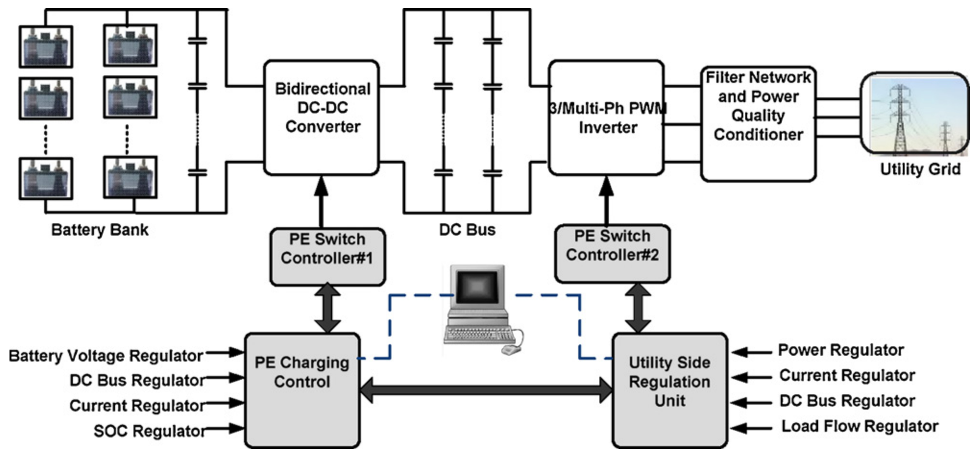

Fig. 16. BESS charging/discharging network via PE links.

The schematic of a BGS is shown in Fig. 15 a BGS unit is supplying a 3-phase AC–AC converter system as shown in the figure. There is a HFAC link in concatenation with the AC converter unit. At the load end, there is 3-phase AC–AC converter for power regulation and to supply the desired power to the utility grid. The reference power and nominal voltage of utility would decide the machine torque and the PWM signal for the switch controllers. In other configurations, there can be other multiphase AC–AC converter units used for the purpose of power utilization and delivery to the grid [55–57].

6. Energy storage systems for RERs

6.1. Battery energy storage systems: BESS and PE network

Battery storage units which produce DC signal must be converted to AC before supplying the grid by means of PE mediums. Battery combinations are connected series/parallel combinations based on the voltage and current requirements. PE interfaces such as DC–AC inverters as well as DC–DC converters are connected to the BESS systems for supplying normal load demand at the utility end. The basic unique feature of the energy storage system that the PE interfaces must be bidirectional to be able to send and receive power to the grid. In Fig. 16 a BESS is shown where battery storage bank followed by the PE converters are connected.

PE topologies and interfaces based on the BESS can be of different types based on the number of cascaded stages in the conversion system, galvanic isolations, types of converters/inverters and utility requirements. One of the common two-stage topologies for the BESS would consist of DC–AC VSI stage and a DC–DC converter stage. Other typical topology would have galvanic isolation between the input and output terminals and step up or down the output voltage with the use of high frequency transformer. A regulated DC bus voltage is maintained by the PE interfaces both during the sending and receiving of power by the BESS. In Fig. 16 as DC–DC bidirectional conversion stage followed by a 3-phase inverter stage is shown. Based on the status of the BESS such as either sending or receiving, the topology of the network would vary and hence the control algorithm would change accordingly. The switch control signal is generated based on the BESS nominal voltage, the reference power and the SOC of the batteries [58–63].

6.2. Flywheel energy storage systems: FESS and PE network

Flywheel systems often use PE interfaces for regulating the power output from the flywheels. A 3-pahse motor/generator set is typically used to convert mechanical energy to the electrical energy which is regulated by PE interfaces for delivering power of the utility grid. Conversely the PE interface acts to deliver power from the utility back to the flywheel for recharging and spin up. The common structure of the PE interface of a FESS would consist of a DC–AC grid connected inverter and an AC–DC bidirectional converter with a common DC-bus incorporated in-between.

During the discharge mode flywheel converter would work as a rectifier unit and the grid converter works as an inverter circuit to control the grid current by PWM method. Conversely, during the charging of the flywheel, the rectification as well as inversion

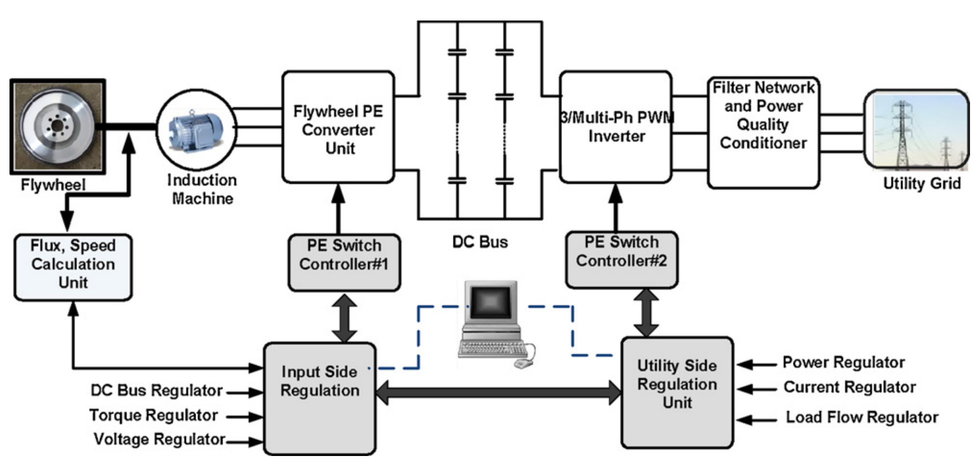

Fig. 17. FESS charging/discharging interfaces via PE networks.

processes are reversed and the power is made to flow from the grid to the flywheels. A generic picture of FESS based RE utilization in conjunction with PE interfaces is shown in Fig. 17.

In order to regulate the DC bus voltage, required output power and the active power values are calculated. FESS torque for the wheels is generated based on this reference power. The calculated power from the loops generates the desired current signal for the current controllers. The current control loops are finally implemented to generate the duty cycle for the PWM converters for delivering the desired power for the utility grid. Depending on the utility connections the rectification and inversion stages can be of single, three, or multiphases. In some FESS, a high frequency AC link, (HFAC) can be incorporated in between the PE stages between the input and the output stages [62–67].

7. Conclusions

Latest advancements in power electronic technology play a great role in the generation, integration, and transmission of renewable energy resources to a wide extent. The capacity of renewable energy generation has multiplied manifolds in the past decade to the higher end technology developments happening in the field of power electronics and motor drives as discussed in the paper. It is being possible to develop sophisticated power electronics technology with highest generator rating to optimize the generation and transmission of renewable energy resources. Growth of semiconductor electronics led to the development of switching devices for big power devices with higher ratings. Numerous multistage converter and inverter topologies are summarized in the paper. Various modulation techniques for control of the power converter topologies are illustrated. Contribution of the advancements of motor drives in the generation of renewable energy resources are discussed in here. Generation of various renewable energy sources such as solar, wind, biomass, fuel cell in tandem with power electronic interfaces are elaborated in the paper. Energy storage systems such as battery and flywheel systems with bidirectional power transfer capability are discussed in the paper. Overall, the contribution of power electronics and motor drives in the field of renewable energy generation, storage, and transmission is enormous.

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